

# Asymmetric Origin for Gravitino Relic Density in the Hybrid Gravity-Gauge Mediated Supersymmetry Breaking

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## Abstract

We propose the hybrid gravity-gauge mediated supersymmetry breaking where the gravitino mass is about several GeV. In such kind of scenario, the strong constraints on the supersymmetry viable parameter space from the CMS and ATLAS experiments at the LHC can be relaxed due to the heavy colored supersymmetric particles, and it is consistent with null results in the dark matter (DM) direct search experiments such as XENON100. In particular, the possible maximal flavor and CP violations from the relatively small gravity mediation may naturally account for the recent LHCb anomaly. In addition, because the gravitino mass is around the asymmetric DM mass, we propose the asymmetric origin of the gravitino relic density and solve the cosmological coincident problem on the DM and baryon densities  $\Omega_{\text{DM}} : \Omega_b \approx 5 : 1$ . The gravitino relic density arises from asymmetric metastable particle (AMP) late decay. However, we show that there is no AMP candidate in the minimal supersymmetric Standard Model (SM) due to the robust gaugino/Higgsino mediated wash-out effects. Interestingly, AMP can be realized in the well motivated supersymmetric SMs with vector-like particles or continuous  $U(1)_R$  symmetry. Especially, the lightest CP-even Higgs boson mass can be lifted in the supersymmetric SMs with vector-like particles.

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## I. INTRODUCTION AND MOTIVATION

The most natural solution to the gauge hierarchy problem is supersymmetry (SUSY). In the Minimal Supersymmetric Standard Model (MSSM) with  $R$ -parity, the Standard Model (SM) gauge couplings can be unified at about  $2 \times 10^{16}$  GeV, which strongly indicates the Grand Unified Theories (GUTs). And there is a dark matter (DM) candidate, which is the lightest supersymmetric particle (LSP) such as neutralino, sneutrino, or gravitino, etc. Thus, the supersymmetric SMs (SSMs) are anticipated among the most promising new physics beyond the SM. However, the CMS [1] and ATLAS [2] experiments at the LHC have given strong constraints on the viable supersymmetry parameter space, in particular, the colored supersymmetric particles (sparticles) such as squarks and gluinos must be heavy at least around the 1 TeV or larger. In addition, the LHCb experiment [3] have recently observed large  $\Delta A_{CP}(A_{CP}(D^0 \rightarrow K^+ K^-) - A_{CP}(D^0 \rightarrow \pi^+ \pi^-))$ . Also, after years of effort the direct DM detection brings confusing results, as well as a strong exclusion line from XENON100 [4] that pushes the lightest neutralino LSP as a DM candidate to a quite embarrassing circumstances [5].

To understand these results, we may have to re-examine the basic assumptions underlying the experimental searches: (1) the CMS and ATLAS collaborations have mainly studied the viable supersymmetry parameter space in the mSUGRA where the squarks and gluinos might be relatively light; (2) the assumption for the DM direct detection experiments is the weakly interactive massive particle (WIMP) scenario where the DM density can be reproduced naturally. In fact, the relatively heavy squarks and gluinos can be realized elegantly in the gauge mediated supersymmetry breaking (GMSB) (see the review [6] and references therein), where the gravitino is a dark matter candidate. Thus, it is not surprising that we have null results at the LHC and XENON100. However, gauge mediation is flavour blind, and then we can not explain the LHCb recent results. The simple solution is that we turn on the gravity mediation which can induce the flavour and CP violations. Because of the strong constraints on flavour violating neutral current FCNC and on the electric dipole moments for neutron and electron, such gravity mediation must be small. Thus, we propose the hybrid gravity-gauge mediated supersymmetry breaking where the gravitino mass is a few GeV.

Moreover, there is a well-known coincident puzzle between the DM and baryon densities. In our Universe today, the ratio of the DM and baryonic matter energy density is at the order one, *i.e.*,  $\Omega_{\text{DM}} h^2 : \Omega_b h^2 \approx 5 : 1$ . The asymmetric DM (ADM) framework [7] provides a very good solution, and it predicts the dark matter mass around 5 GeV. Thus, if the gravitino relic density has asymmetric origin, we can solve the coincident problem. In this paper, we propose that the gravitino acquires the relic density from asymmetric metastable

particle (AMP) late decay. For simplicity, we called such gravitino as the “asymmetric” gravitino. This proposal combines  $\tilde{G}$  late decay production [8, 9] with the asymmetric DM (ADM) framework [7]. And then it inherits both merits. Especially, just as the ADM the “asymmetric” gravitino is predicted to have a mass around 5 GeV. Therefore, the SUSY breaking should be mediated dominantly by GMSB but nearly hit the maximal flavor and CP violations from democracy gravity mediation. In this paper, we will show that there is no AMP candidate in the MSSM due to the robust gaugino/Higgsino mediated wash-out effects. Interestingly, AMP can be realized in the well motivated supersymmetric SMs with vector-like particles or continuous  $U(1)_R$  symmetry. Note that the ATLAS and CMS Collaborations have reported an excess of events for the SM-like Higgs boson with mass around 126 GeV and 124 GeV, respectively [10, 11], the supersymmetric SMs with vector-like particles are very interesting since we can lift the lightest CP-even Higgs boson mass [12–15].

The paper is organized as follows. In Section II we study the general conditions that such a scenario can be realized. In Section III we consider two typical AMP candidates in the supersymmetric SMs with vector-like particles or continuous  $U(1)_R$  symmetry. Our conclusion is in Section IV.

## II. GRAVITINO RELIC DENSITY FROM AMP LATE DECAY

### A. Natural DM: ADM versus WIMP

Theoretically, ADM provides a very natural, simple, and predictive framework to understand the relic density of DM [7, 16, 17]. And it shows prominent advantage compared to the well accepted WIMP framework. First of all, it is well known that the ADM resolves the coincidence problem (or naturalness problem). Concretely speaking, the DM and baryon number densities are dominated by their asymmetric components, and a relation on their number densities are obtained dynamically  $n_D - n_{\bar{D}} = C(n_B - n_{\bar{B}})$ , where  $C \sim 1$  depends on models [42]. As a result, their relic density take ratio

$$\frac{\Omega_{\text{DM}} h^2}{\Omega_B h^2} = \frac{m_D(n_D - n_{\bar{D}})}{m_p(n_B - n_{\bar{B}})} = C \times \frac{m_D}{m_p}. \quad (1)$$

The coincidence puzzle is resolved by a single parameter, the mass ration  $m_D/m_p \sim \mathcal{O}(5)$ .

Next, maybe it is more interesting to regard it as an elegant mechanism to generate DM relic density. On the one hand, a WIMP relic density is determined by DM annihilating process freeze-out, and typically leads to relic density scales as [18]

$$\Omega_{\text{DM}} h^2 \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_D^2}{g_D^4}, \quad (2)$$

with  $g_D$  the effective DM and light particle coupling. Although the above equation is merely an indicative estimation, it reveals a fact that in the WIMP scenario probably the right DM relic density is sensitive to the fundamental parameters (higher powers of parameters), or even requires large fine-tuning, saying the well-tempered neutralino DM scenario in the MSSM [19]. In this regard ADM is more natural, because its relic density is almost only linear to its mass and irrespective of the concrete value of couplings, neither does not have to keep track of detail cosmological evolution via Boltzmann equations.

Finally, aside from the power to predict its mass, by construction the ADM also predicts the DM carries (at least highly good) continuous conservative charge. For details, please see a recent work on the charge breaking term effect in the Ref. [20]. However, the most popular and natural DM candidates like neutralino, gravitino and real scalar can not be the ADM candidate since they are self CP-conjugate states, and there is no continuous symmetry for them. Thus, how to let these Majorana fermion or real scalar DM candidates share the great merits of ADM is very interesting and worthy of effort. In this paper, we consider gravitino as an example.

## B. Gravitino Relic Density from AMP

The essential point of ADM lies in that its number density is dynamically related to the baryon number density. In this regard, it is tempting to conceive that the DM obtains its number density from an asymmetric metastable particle late decay, rather than itself participates in the asymmetry transferring process. Apparently, in this framework the aforementioned DM candidates can enjoy the ADM merits.

Essentially, this mechanism to account for DM relic density is the combination of ADM and non-thermal dark matter production. By construction, there are two basic assumptions inherited from them:

- The DM candidate  $\chi$  has negligible thermal relic density. If it is used to enter the plasma and freezes out at some temperature  $T_f \sim m_\chi/20$ , it should leave with inappreciable relic density. On the other hand, if it never undergoes thermal equilibrium, such as  $\tilde{G}$ , its production after inflation should be highly suppressed.
- An AMP late decays to the DM at  $\tau_{\text{AMP}}$ : for a superWIMP-like DM such as gravitino, it is not constrained directly except for some cosmology consideration; while for the WIMP-like DM it is required the decay happens after DM thermal decoupling:  $\tau_{\text{AMP}} \gg H^{-1}(T_f) \simeq 0.3g_*^{-1/2} M_{Pl}/T_f^2$ , equivalently the decay rate is highly suppressed

$$\Gamma_{\text{AMP}} \ll 3.8 \times 10^{-18} \times \left( \frac{m_{\text{AMP}}}{100\text{GeV}} \right)^2 \text{ GeV}. \quad (3)$$

Comments are in orders. First, this scenario extends the region of DM that shares the merit of ADM. Next, the AMP mass is not constrained, since only its asymmetric number density  $n_X$  is important. Finally, the non-annihilating bosonic ADM is unfavored today by astronomical objects [21], whereas non-annihilation is not required here. Connecting to the SUSY-breaking, gravitino is a special candidate to this scenario [43].

In the framework of supergravity, the gravitino mass is uniquely determined by the scale of SUSY breaking in the hidden sector,  $\sqrt{F}$

$$m_{\tilde{G}} = \frac{F}{\sqrt{3}M_{Pl}}, \quad (4)$$

where  $M_{Pl} \simeq 2.14 \times 10^{18}$  GeV is the reduced Planck scale. And  $10^5 \text{ GeV} \lesssim \sqrt{F} \lesssim 10^{11} \text{ GeV}$ , depending on the scheme of SUSY breaking mediation. So the gravitino mass varies from the eV to TeV region, which is highly model dependent. But if we consider  $\tilde{G}$  is the dominant DM component, it is possible to fix  $m_{\tilde{G}}$ . In turn, it has deep implication to SUSY breaking as well as its mediation mechanism. In the following, we present some ways to determine or predict  $m_{\tilde{G}}$ :

- The original supersymmetric DM candidate is nothing but gravitino, proposed by H. Pagels and J. R. Primack [23]. They have shown that for the thermal gravitino, its relic density is simply given by

$$\Omega_{\tilde{G}}^{th} h^2 \simeq 0.1 \left( \frac{m_{\tilde{G}}}{100 \text{ eV}} \right) \left( \frac{106.75}{g_{*S,f}} \right), \quad (5)$$

which determines  $m_{\tilde{G}} \sim 100 \text{ eV}$ , point to low scale SUSY breaking. However, astrophysical observation excludes such hot (total) DM [24]. Even stronger, the combination of WMAP, CMB and Lyman- $\alpha$  data excludes  $\tilde{G}$  to make up of whole DM, irrespective of its mass (see Ref. [25] and reference therein).

- Non-standard cosmology history, for example in the non-thermal production recurring to tune reheating temperature [26], is able to save it. For non-thermal  $\tilde{G}$  production its thermal relic density via scattering is linearly proportional to the reheating temperature  $T_R$  [27]

$$\Omega_{\tilde{G}}^{th} h^2 \simeq 0.03 \left( \frac{10 \text{ GeV}}{m_{\tilde{G}}} \right) \left( \frac{M_3}{3 \text{ TeV}} \right)^2 \left( \frac{T_R}{10^6 \text{ GeV}} \right), \quad (6)$$

which is valid at  $T_R < T_f$  with  $T_f$  the thermal gravitino decoupling temperature. This kind of UV sensitivity is never a good property since we have no data to trace back to so early Universe, consequently  $T_R$  is undetectable rendering the unique prediction on gravitino mass impossible.

- Turning to our scenario inspired by naturalness. First, the thermal production is assumed to be sub-dominated due to rather low reheating temperature or lighter gluino mass. Then the AMP with only asymmetric relic density decays to  $\tilde{G}$  leads to

$$m_{\tilde{G}} = \frac{\Omega_{\text{DM}} h^2}{\Omega_B h^2} \frac{n_B}{n_{\text{AMP}}} m_p. \quad (7)$$

Just as the ADM,  $n_{\text{AMP}} \sim n_B$  is related to the baryon asymmetry (see Eq. (1)), thus the gravitino mass generically is predicted to be several GeVs.

We have to emphasize that, the “asymmetric” gravitino scenario completely solves the naturalness problem involving the DM from two aspects: (A) In the spirit of ADM, it reveals the cosmological coincident puzzle; (B) But most ADM are not thoroughly natural on account of the ADM mass since it is put by hand rather than having non-dynamical origin. By contrast, the gravitino mass is dynamically generated tied with dynamical SUSY breaking. From this point of view, this scenario should receive enough attention.

### C. Hybrid Gravity-Gauge Mediated Supersymmetry Breaking

In this subsection, we simply assume the AMP late decay to gravitino and study its implication. And in the next subsection we shall discuss the conditions for viable AMP in details.

A gravitino mass of several GeVs has far-reaching physical implication to SUSY. Concretely speaking, it implies that the SUSY-breaking is mediated by the hybrid of gravity mediation and gauge mediation (in the anomaly mediation the gravitino mass is around tens of TeVs). To see it, notice that the gravity mediation typically contributions to soft terms at the order of gravitino mass

$$m_{\tilde{f}}^2 \simeq m_{\tilde{G}}^2, \quad A \simeq M_\lambda \simeq m_{\tilde{G}}. \quad (8)$$

where  $m_{\tilde{f}}$ ,  $M_\lambda$  and  $A$  are sfermion masses, gaugino masses, and trilinear soft terms, respectively. Phenomenologically, the  $m_{\tilde{f}} \sim M_\lambda \sim \mathcal{O}(500)$  GeV, so the gravity mediation fails to provide the sufficient soft mass source to the sparticles. This is required since there may exist large FCNC and CP violations in the supersymmetry breaking soft terms via gravity mediation. We have to turn to the GMSB [6], where the gravitino mass is

$$m_{\tilde{G}} = \frac{1}{\sqrt{3}} \frac{\Lambda M_{\text{mess}}}{M_{\text{Pl}}}. \quad (9)$$

The realistic soft spectra require  $\Lambda = F/M_{\text{mess}} \sim 10^4 - 10^5$  GeV. Consequently, a 5 GeV gravitino implies that the messenger scale is close to the GUT scale  $M_{\text{mess}} \sim 10^{14}$  GeV.

Although flavor from the GMSB falls into the minimal flavor violation (MFV) assumption, the anarchical soft mass terms from gravity mediation (see Eq. (8)) reaches the maximal flavor violation. This is very interesting since it implies that this hybrid mediation scenario is testable from the future high-precision FCNC experiments in the B-factories and the LHCb via  $c \rightarrow u$ ,  $b \rightarrow d, s$ , while the  $t \rightarrow c, u$  decays can be explored at the LHC [28].

In practice, the decay  $c \rightarrow u\bar{q}q$  may have left tracks in the recent LHCb experiment. It reports a measurement of CP asymmetry in  $D$  meson decay  $A_{CP}(D^0 \rightarrow K^+K^-) - A_{CP}(D^0 \rightarrow \pi^+\pi^-)$ , with measured difference deviating from the SM predication  $3.5\sigma$  evidence [3]. This results can be attributed to the direct CP violation, and to interpret the anomaly with new physics it is required to generate large CP violation in decay meanwhile suppressing the CP violation in  $D^0 - \bar{D}^0$  mixing [29]. Surprisingly, our framework just provides such a new physics. The points can be found in the Ref. [30]. Briefly speaking, in the SUSY with flavor violation, in up squark-gluino loops, the up squark mass insertion from  $\delta_{LR} \equiv (\tilde{m}_{LR}^{2u})_{12}/\tilde{m}^2$  ( $\tilde{m}$  is the common squark mass) contributes both to the Wilson coefficients of dipole operator (contributing to direct CP violation) and the operators generating  $D^0 - \bar{D}^0$  mixing, but the former is enhanced by  $m_{\tilde{g}}/m_c$  whereas the latter is not. Consequently, it avoids the bound naturally, but we leave the quantitatively study elsewhere.

#### D. Scattering Induced Charge Wash-Out Effects

The existence of AMP is highly non-trivial, but unfortunately such an attractive possibility does not exist in the MSSM or its simple extension. To see it, we consider a system with particle (1) and anti-particle (2), and they can change individual number density via the following annihilation and scattering process

$$12, 21 \leftrightarrow f\bar{f}, \quad 11 \leftrightarrow ff, \quad 22 \leftrightarrow \bar{f}\bar{f}, \quad 1\bar{f} \leftrightarrow 2f. \quad (10)$$

It is a common situation for the MSSM sparticles such as sfermions, charginos, see the Fig. 1 for typical processes. That is to say, in general the sparticle charge is washed-out during freeze-out. The reason is easy to understand, for the SM charged particles, there are vertex like particle-sparticle-gaugino/Higgsino, from gauge or Yukawa interactions, then the Majorana neutralinos mediate charge violation scattering.

The above two source of violation can be traced back to the  $U(1)_R$  symmetry in the low energy theory. This continuous symmetry does not communicate with SUSY, and in the superspace it is defined as ( $W$  is the superpotential,  $\theta$  as Grassman coordinate)

$$(d\bar{\theta})\theta \rightarrow e^{i\alpha}(d\bar{\theta})\theta, \quad (d\theta)\bar{\theta} \rightarrow e^{-i\alpha}(d\theta)\bar{\theta}, \quad W \rightarrow e^{2i\alpha}W. \quad (11)$$



Then for a chiral superfield  $\Phi$  with  $U(1)_R$  charge  $r$  (also the charge for the lowest component), its  $\theta$ -component carries charge  $r - 1$ . Especially, gaugino must carry  $U(1)_R$  charge  $-1$ . Then the effective vertices from gauge interactions,  $\mathcal{O}_{SCV} = \tilde{f}\tilde{f}\tilde{f}\tilde{f}$  break  $U(1)_R$  charge by negative two units, which can be generated with insertions of the Majorana gaugino mass terms. While the Yukawa coupling terms in the superpotential does not breaks  $U(1)_R$ , their contributions to such operators are always there. But their strengths can be controlled by Yukawa couplings (by accidently, in the exact  $U(1)_R$  MSSM, the  $\mu$ -term will be forbidden out of other consideration, and we shall turn to it later).

To investigate the phenomenon more systematically, we consider the charge evolution through Boltzmann equations. We define the number density factoring out the chemical potential

$$n_1^{eq} = az^{3/2}e^{-z}e^{\xi_1(z)}, \quad n_2^{eq} = az^{3/2}e^{-z-\Delta m/T}e^{\xi_2(z)}, \quad (12)$$

where  $\xi_i \equiv \mu_i/T$  with  $\mu_i$  the chemical potential and  $\Delta m = 0$  here. With the help of this notation, the Boltzmann equations can be written in the following form

$$-zy'_1 - zy_1 \frac{Y'_{eq}}{Y_{eq}} = (y_1 y_2 - 1) \frac{\Gamma_{12}}{H} + (y_1^2 - e^{-2\xi_f}) \frac{\Gamma_{11}}{H} + (y_1 e^{-\xi_f} - y_2 e^{\xi_f}) \frac{\Gamma_{1\bar{f}}}{H}, \quad (13)$$

$$-zy'_2 - zy_2 \frac{Y'_{eq}}{Y_{eq}} = (y_1 y_2 - 1) \frac{\Gamma_{12}}{H} + (y_2^2 - e^{2\xi_f}) \frac{\Gamma_{22}}{H} + (y_2 e^{\xi_f} - y_1 e^{-\xi_f}) \frac{\Gamma_{2f}}{H}, \quad (14)$$

where  $\Gamma_{ij} = \gamma_{ij}/n_{eq}$ ,  $Y'_{eq}/Y_{eq} = 3/2z - 1 \simeq -1$ . The second collision term purely destroys the DM charge. When  $\Gamma_{ij} \gg H$ , the corresponding reaction enters chemical equilibrium, by contrast ignorable.

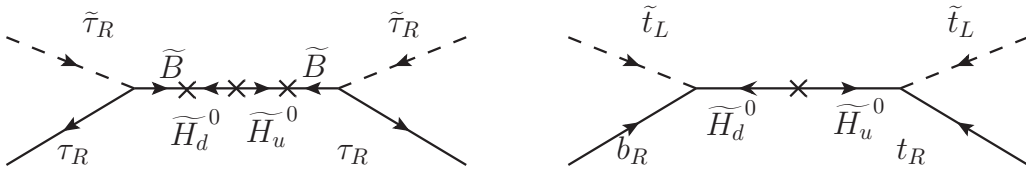


FIG. 1: The gaugino and Higgsino mediated sparticle charge washing-out processes.

Notice that the last reaction does not change the total number density of the system, but transfers particle and antiparticle. This is highly relevant to a system with asymmetry. Especially, at the non-relativistic region of DM, annihilation rate is power suppressed by the number density, whereas the scatter is still very effective

$$\frac{\langle \sigma v \rangle_{anni}}{\langle \sigma v \rangle_{scat}} \sim \frac{(n_1^{eq})^2 \sigma_{anni}}{(n_1^{eq}) \sigma_{scat}} \sim n_1^{eq} \sim z^{3/2} e^{-z}. \quad (15)$$



If the scattering and annihilation cross sections are not hierarchal different, the annihilation rate at  $z \sim z_f \simeq 25$  is suppressed by 9 orders (in fact, it is nothing but the kinetic decoupling happens much later than chemical decoupling [31]). So during the freeze-out of annihilation even long after that, it maintains the chemical equilibrium between 1, 2 and the  $f, \bar{f}$ , and gives a strong constraint

$$\xi_1 - \xi_f = \xi_2 + \xi_f. \quad (16)$$

Generically, the particles in the plasma have tiny asymmetry at the order of baryon asymmetry, thus for relativistic species

$$\frac{n_f - n_{\bar{f}}}{n_\gamma} \sim \frac{n_b - n_{\bar{b}}}{n_\gamma} = \eta \Rightarrow \frac{g_f}{2} \frac{\pi^2}{3} \xi_f \sim \eta \sim 10^{-10}. \quad (17)$$

To decouple the robust scattering process, the particle-antiparticle ratio is fixed to be equal to

$$r_{eq} = \left( \frac{n_1^{eq}}{n_2^{eq}} \right) = e^{\xi_1(z) - \xi_2(z)}. \quad (18)$$

And to decouple such robust reaction, the corresponding cross section has to be several orders suppressed. For example, if the scattering process decouples at the weak scale, it is required

$$T^3 \sigma_{sc} < H(T) = 1.66 g_*^{1/2} T^2 / M_{\text{Pl}}|_{T=100 \text{ GeV}}. \quad (19)$$

Thus,  $\sigma_{sc}$  is smaller than  $10^{-10}$  pb, which are suppressed by about 10 orders comparing to the WIMP annihilation cross section. Without special treatment, it is an impossible mission in the MSSM.

There is a loop-hole to obtain the above conclusion:  $f$  is relativistic when  $\tilde{f}$  becomes cold. Nevertheless, it is not always the case in the MSSM. If so, when  $f$  is decoupling,  $\tilde{f}$  also becomes non-relativistic, implying its asymmetry is almost maximal

$$0.3 g_f z^{3/2} e^{-z+\xi_f} (1 - e^{-2\xi_f}) \sim \eta \Rightarrow 0 < \xi_f \simeq z - 10. \quad (20)$$

So the above conclusion does not hold. For example, the  $W^\pm$  vector bosons and charged Higgs particles  $H^\pm$  have comparable (even larger) masses to their superpartners, the chargino system consisting of  $(\tilde{W}^\pm, H_u^\pm, \tilde{H}_d^\pm)$ . However,  $W^\pm/H^\pm$  mediates scattering processes such as  $\tilde{C}_1^\pm + u \rightarrow \tilde{N}_1 + d$  with  $\tilde{C}_1, \tilde{N}_1$  denoting the lightest chargino and neutralino respectively. Even if the  $M_{\tilde{C}_1} < M_{\tilde{N}_1}$  can be attained in some corner of parameter space, they are still quite degenerate. As a result the scattering can proceed fast and lead to  $\xi_{\tilde{C}_1} = \xi_{d_L} - \xi_{u_L}$ , therefore no asymmetry left as before.

Another apparent such candidate is the stop-top system where the lighter stop  $\tilde{t}_1$  can be lighter than the top quark in some cases. However, even we do not consider the effective  $\tilde{t}_1 t \rightarrow \tilde{t}_1^* \bar{t}$  at the tail of Boltzmann distribution, the robust  $\tilde{t}_1 c \rightarrow \tilde{t}_1^* \bar{c}$  via CKM mixing can only suppressed to  $\lambda^8 \sim 10^{-7}$  with  $\lambda \simeq 0.22$  the Cabbibo angle. So several orders are needed to suppress it. In light of the above arguments, we safely draw the conclusion: in the MSSM no AMP can be accommodated.

### III. AMP IN THE MSSM EXTENSIONS

In light of the general lessons from the previous Section, to construct model with AMP, the simplest way is just to introduce extra vector-like matters to the MSSM. Interesting, such models have been investigated out of some other motivation. But based on the symmetry analysis,  $U(1)_R$ -symmetric MSSM (MRSSM) provides very good framework to realize “asymmetric” gravitino also.

#### A. AMP Inspired vMSSM

The MSSM extended with weak-scale vector-like particle (vMSSM) often arises in model building [32, 33], for example, as a consequence in string theory construction [32] or extending MSSM with anomaly-free group such as  $U(1)_R$  [13]. The presence of such light particles at the low energy brings rich and prominent phenomenology, *e.g.*, lifting the lightest CP-even Higgs boson mass [14] and accordingly solving the little hierarchy problem [12, 15]. In this work, we primarily investigate the surviving of charge asymmetry in this framework.

The vMSSM has different versions depending on what vector-like matters are introduced. We require that the particle content is consistent with GUTs, for example, the  $SU(5)$  GUT. As a minimal attempt, consider  $\text{MSSM} + \bar{5}_4 + 5_4 + \bar{1}_4 + 1_4$ , where  $5_4 = (D_4^c, L_4)$  with vector-like partner implied with a bar. Decomposed into the MSSM, their SM gauge group quantum numbers are  $D_4^c = (3, 1, -1/3)$ ,  $L_4 = (1, 2, -1/2)$ ,  $N_4 = (1, 1, 0)$ . For simplicity, the index “4” will be implied while the ordinary matter family index are denoted with  $i = 1, 2, 3$ . Moreover, to not be excluded, the vector-like pair have large supersymmetric mass terms. Then the model takes a form of

$$W_{Z_2} \supset (y_{ij}^U Q_i H_u U_j^c + y_{ij}^D Q_i H_d D_j^c + y_{ij}^E L_i H_d E_j^c) + (k_N H_u L \bar{N} - h_N H_d \bar{L} N), \\ + (M_D D^c \bar{D}^c + M_L L \bar{L} + M_N N \bar{N}), \quad (21)$$

$$-V_{soft} \supset \sum_{\phi_i=D, \bar{D}, \dots} m_{\phi_i}^2 |\phi_i|^2 + (B_D D \bar{D} + B_L L \bar{L} + B_N N \bar{N} + h.c.) \\ + (A_k H_u L \bar{N} - A_h H_d \bar{L} N + h.c.). \quad (22)$$

Especially, the term  $k_N H_u L \bar{N}$  with  $k_N \sim 1$  is the key element of this kind of models, which helps to increase the Higgs boson mass. We will find in the following on our purpose that this term is crucial as well.

First, large  $k_N$  helps to get lighter singlet. The fermionic color particles  $(D^c, \bar{D}^c)$  and the charged component in the  $(L, \bar{L})$  (we denote  $L = (\nu_L, e_L)$ ) form Dirac particles with mass respectively  $M_D$  and  $M_L$ , putative close to the TeV scale. In the GMSB, their superpartners are even heavier, by virtue of large soft mass square while the soft bilinear term  $B_{D,L,N}$  (reduce eigenvalues) are generated at loop level and then are suppressed. Especially for the singlet without gauge interactions  $B_N \sim 0$  is a good approximation. So in the following we focus on the mass eigenstates of mixed vector-like SM singlet system. For the (Dirac) fermions, in the basis spanned by  $(\nu_L, N)$ , the Dirac mass matrix is

$$M_F = \begin{pmatrix} M_L & k_N v_u \\ h_N v_d & M_N \end{pmatrix}. \quad (23)$$

Since we do not need the precise value of AMP mass, the reasonable approximation can be made to obtain their superpartner masses. We work on a mild hierarchy  $k_N v_u \lesssim M_N \lesssim M_L$ , and consequently the mixing is small, which leads to isolated singlet system  $(\bar{N}, N)$  (the  $\bar{\nu}_L, \nu_L$  pairs with mass  $\simeq M_L$ ). The  $B_N$  can be safely ignored as well, and then the scalar mass squares are simply given by

$$m_{\tilde{N}_1}^2 \simeq M_N^2 + m_{\tilde{N}}^2, \quad m_{\tilde{N}_2}^2 \simeq M_N^2 + m_{\tilde{N}}^2. \quad (24)$$

The soft mass terms for  $(\tilde{\tilde{N}}, \tilde{N})$  vanish at the UV boundary and are generated negatively by the renormalization group equation (RGE) effect. So we have

$$m_{\tilde{\tilde{N}}}^2 \sim - \left( \frac{k_N^2}{16\pi^2} \log \frac{M_{\text{GUT}}}{M_N} \right) m_{\tilde{L}}^2, \quad (25)$$

which is large due to the order one  $k_N$ . Similar results hold for  $m_{\tilde{N}}^2$ , but we assume that  $h_N$  is much smaller so as to make  $m_{\tilde{N}}^2 \ll M_N^2$  (note that the Higgs boson mass is not sensitive to  $h_N$ ). Then large mass splitting between  $\tilde{\tilde{N}}$  and  $\tilde{N}$  are generated naturally, making only the former (even much) lighter.

Next, the  $k_N$  term also provides a sufficiently effective channel to let the AMP annihilate away the symmetric part. For example, the AMP annihilate into a pair of Higgs particles via the term  $|F_L|^2 \supset k_N^2 |\tilde{\tilde{N}}|^2 h^2 / 2$  with a thermal averaged cross section roughly

$$\sigma v \sim \frac{1}{8} \frac{k_N^4}{32\pi} \frac{1}{m_{\tilde{N}_1}^2} \sim 10 \text{ pb}, \quad (26)$$

for  $m_{\tilde{N}_1} \simeq 100 \text{ GeV}$ . It is large enough to annihilate away the symmetric part [16]. By the way, if  $\tilde{N}_1$  is even much lighter, the  $s$ -channel Higgs mediated process  $\tilde{N}_1 \tilde{N}_1^* \rightarrow W^+ W^- / \bar{f} f$  can always provide large annihilating rate with resonance.

The model has some phenomenological demerits and requires improvements. At first, the vector-like mass terms are introduced by hand, but they may share common origin as the  $\mu$  parameter. For example, in the GMSB the weak scale can be generated in the presence of an intermediate scale, such as the spontaneously breaking scale of  $U(1)_{PQ}$ , which sets in the window  $f_{PQ} \sim 10^9 - 10^{12}$  GeV. Thus, the supersymmetric mass terms are generated via high-dimension operators [34]

$$\frac{X^2}{M_{\text{Pl}}} (\lambda_4 5_4 \bar{5}_4 + \lambda_h 5_u \bar{5}_d + \lambda_1 1_4 \bar{1}_4), \quad (27)$$

where  $X$  is the PQ-axion superfield carrying (normalized) PQ-charge  $-1$ , and it develops a vacuum expectation value around  $f_{PQ}$ . So the supersymmetric mass terms are

$$\mu = \lambda_h f_{PQ}^2 / M_{\text{Pl}}, \quad M_4 = \frac{\lambda_4}{\lambda_h} \mu, \quad M_1 = \frac{\lambda_1}{\lambda_h} \mu. \quad (28)$$

The operator coefficients are order one with moderately smaller  $\lambda_1$  in this paper.

Next, this vMSSM conserves an exact  $Z_2$ -parity that acts only on exotic particles, and forbids the mixings between vector-like particles and MSSM matters. Consequently, it suffers from acute cosmological problem, on account of significant (quasi) stable colored relics are definitely excluded by observations. Even worse, it renders the ambitious “asymmetric” gravitino scenario stillborn from two aspects: first, the lightest particle from the dark sector (refers to vector-like particles) is stable rather than decay; Next, in the exact  $Z_2$  case the dark number is conserved exactly, so no final asymmetry can be generated during the Universe evolution, except for primeval dark number is generated (for example via common decay). But in this paper we stick on dark sector asymmetry is obtained via the re-distribution of visible sector asymmetry.

So it is necessary to introduce the  $Z_2$ -violation mixing terms, consequently the ordinary  $R$ -parity is the unique low energy symmetry. On our purpose, we consider the following soft  $Z_2$ -breaking terms:

$$W_{Z_2} \supset \epsilon_i^u H_d Q_i U^c + \epsilon_i^e H_d L E_i^c + \epsilon_i^N H_u L_i \bar{N}, \quad (29)$$

where  $\epsilon_i \ll 1$ . This requirement does not introduce acute naturalness problem since the Yukawa structure in the MSSM is also hierarchical, and one may expect flavor symmetry to account for this naturalness problem but beyond this work. Moreover, these new parameters (including new vector-like mass terms) effectively do not exacerbate the parameter space of the MSSM, and then we do not care their concrete values aiming at tuning out some observables.

We have to further discuss  $\epsilon_i$  from several aspects. At first,  $\epsilon_i$  should be sufficiently small so as not to induce large flavor violation. Next,  $\epsilon_i^N$  are further constrained by reviving charge

washing-out stored in the  $\tilde{N}$ . These terms  $(\epsilon_i^N v_u)\nu_i\tilde{N}$  generate mixings between  $\nu_i$  and  $N$  (whereas  $\epsilon_i^e$  only induce charged state mixings). The Higgsinos contribute to the dominant scattering washing-out processes  $\tilde{N}\nu_i \rightarrow \tilde{N}^*\bar{\nu}_i$  with a rate roughly given by

$$\langle\sigma(\tilde{N}\tilde{N} \rightarrow \nu_i\nu_i)v\rangle \sim \frac{(\epsilon_i^N)^4}{4\pi} \frac{1}{M_{\tilde{H}}^2}. \quad (30)$$

Taking the Higgsino mass  $M_{\tilde{H}} \sim 300$  GeV much heavier than  $m_{\tilde{N}}$ , the cross sections can be suppressed to the order required in Eq. (19) when  $\epsilon_i^N < \mathcal{O}(10^{-3})$ . Finally,  $\epsilon_i^e$  can not be too small, aiming at keeping the dark sector chemical equilibrium with visible sector and decoupling it at proper temperature. It is a non-trivial condition for the storing AMP asymmetry, and we will turn back to this point later.

Alternatively, one can introduce the vector-like particles  $(10_4, \bar{10}_4)$  with  $10_4 = (Q_4, U_4^c, E_4^c)$ , and the discussion proceeds similarly. They couple to the matter fields via the following superpotential

$$\begin{aligned} W_v \supset & 10_a 10_b 5_u + 10_a \bar{5}_i \bar{5}_d + \bar{10}_4 \bar{10}_4 \bar{5}_d + M_{10} 10_4 \bar{10}_4 \\ & \supset Q_a U_a^c H_u + Q_a D_i^c H_d + Q_a E_i^c H_d + \bar{Q}_4 \bar{U}_4^c H_d, \end{aligned} \quad (31)$$

where some terms may have to be forbidden by the PQ-symmetry. In the GMSB  $(\tilde{E}_4^c, \tilde{\bar{E}}_4)$  are lighter than the colored components, but they are heavier than the pure right-handed sleptons  $\tilde{\tau}_R$  in the MSSM and then not the NLSP. The GMSB contribution gives  $m_{\tilde{\tau}_R}^2 \simeq m_{\tilde{E}_4^c}^2 \simeq m_{\tilde{\bar{E}}_4}^2$ , but  $(\tilde{E}_4^c, \tilde{\bar{E}}_4)$  have large supersymmetric mass term, while the splitting due to  $B_E$  is loop suppressed and ignorable, so quite generically they are heavier. However, in more complicated situations the extra colored sparticles can be the NLSP. For example, coupling  $H_u$  to the messengers can lower the soft masses  $m_{\tilde{Q}_4}^2$  and  $m_{\tilde{U}_4^c}^2$ , or similarly we can solve the  $\mu/B_\mu$  problem in the GMSB by coupling them directly to the messenger sector [35]. Thus, one may get more general spectra and allow for extra squark being the NLSP.

To end this subsection, we briefly comment on the impact of an exotic sneutrino AMP to the cosmology. At rather later times (after BBN), at the two-body level the AMP decays to SM neutrino and gravitino:  $\tilde{N} \rightarrow \nu_i + \tilde{G}$ . It is cosmological safe, compared to the SM charged AMP late decay after BBN that injects electromagnetic or hadronic energy. By the way, warm gravitino helps to reduce the power spectrum on small scale [36].

## B. The AMP Asymmetry

We are now at the position to determine the chemical potential of particles in the vMSSM. Most of the discussion is a direct generalization to the ordinary MSSM [37], and comments

on the difference in the vMSSM will be made if necessary. Special attention on the viability of AMP will be paid as well.

In the framework of redistribution of visible sector asymmetry, what we need is to find the temperature  $T_D$ , where the rate of interaction that converts the dark sector asymmetry and visible sector asymmetry falls below the Universe expansion rate  $H(T_D)$ . After that the two sector asymmetries are assumed frozen, then the asymmetric number density of particle  $\phi$  is determined by the chemical potential  $\mu_\phi$  (considering arbitrary  $T$  for generality):

$$\begin{aligned} n_+^{eq} - n_-^{eq} &= f_{b,f}(m/T) \times \frac{gT^2}{6} \mu_\phi, \\ f_{b,f}(m/T) &= \frac{6}{\pi^2} \int_0^\infty dx \frac{x^2 \exp[-\sqrt{x^2 + (m/T)^2}]}{\left(\theta_{b,f} + \exp[-\sqrt{x^2 + (m/T)^2}]\right)^2}, \end{aligned} \quad (32)$$

where  $\theta_{b,f} = \mp 1$  are for a boson and a fermion respectively. The function  $f_{b,f}(m/T)$  denotes the threshold effect for heavy particle in the plasma. In the relativistic limit  $m \ll T$ ,  $f_{b,f} \rightarrow 2, 1$  respectively. Oppositely, a decoupled particle has ignorable asymmetry density as expected.

Comments are in order. The dark number is the generalized  $L$  number. To precisely determine the dark and invisible sector asymmetries, we need to know the electroweak (EW) sphaleron decoupling temperature (denoted as  $T_{sp}$ ) since it is the last process that affects the  $B/L$  number. But for simplicity, we just take  $T_D \sim T_{sp} \lesssim T_c$ , with  $T_c \sim 100$  GeV the EW phase transition critical temperature. It will be justified below, and in fact other possibility will be similar up to threshold effect.

For the ADM or AMP, we only interest in its asymmetric part, in turn we have to work out its chemical potential at different temperature region. It is can be done via the standard method [38]. If a reaction  $A + B + \dots \leftrightarrow C + D + \dots$  is faster than  $H$ , we get a constraint  $\mu_A + \mu_B + \dots = \mu_C + \mu_D + \dots$ , otherwise there is a conservation number. The chemical potential can be obtained by solving all those equations. In the vMSSM, the inventory of fast interactions and corresponding chemical equilibrium equations is

- The  $SU(2)_L$  gauge boson  $W^\pm$  mediates the up and down components in a doublet in equilibrium, which gives

$$[\text{down}]_L = [\text{up}]_L + W^-, \quad W^- = -W^+. \quad (33)$$

Hereafter we denote the particle name and its chemical potential with the same capital letter.

- The gaugino mass terms and the Higgs mixing term ( $B_\mu$ -term) give

$$\widetilde{B} = \widetilde{W}^0 = 0, \quad \widetilde{W}^+ = -\widetilde{W}^-, \quad h_u^+ = -h_d^-. \quad (34)$$

- The neutral gaugino interactions will lead to the identical chemical potentials for the SM particles and their superpartners

$$\begin{aligned}\widetilde{W}^- &= W^- + \widetilde{B} = W^- = -\widetilde{W}^+, \\ \widetilde{f}_L &= f_L + \widetilde{B} = f_L, \quad \widetilde{f}_R = f_R - \widetilde{B} = f_R, \quad \widetilde{h} = h - \widetilde{B} = h,\end{aligned}\tag{35}$$

where  $h$  denotes any Higgs doublet component. It is nothing but the statement that gauginos mediate sparticle charge washing-out processes discussed previously.

- Importantly, even small mixings between vector-like particles and ordinary families can equilibrate them around the weak scale. It is crucial to have an AMP as stressed before. Multi-sources for mixtures in the vMSSM do exist: the Eq. (29) plus the corresponding trilinear soft terms, and flavor universal quadratic soft mass terms  $m_{\widetilde{f}_{i4}} \widetilde{f}_i^\dagger \widetilde{f}_4$ . Concretely speaking, the chemical equilibrium is due to the frequent scattering on the background radiation:  $\widetilde{f}_i + \gamma/W^\pm \leftrightarrow \widetilde{f}_4 + \gamma/W^\pm$ , roughly with a rate

$$n_W \sigma(\widetilde{f}_i W^\pm \rightarrow \widetilde{f}_4 W^\pm) v \sim \frac{(\theta_{i4})^2 g_2^4}{4\pi^3} \frac{T^3}{m_{\widetilde{f}_4}^2}.\tag{36}$$

We will set  $m_{\widetilde{f}_4} \sim 500$  GeV. So it is semi-non-relativistic while the target particle is relativistic around 100 GeV. Compared with  $H(T)$  we know the decoupling temperature  $T < 10^2 (10^{-4}/\theta_{i4})^2$  GeV. In fact, it can be understood similarly as in the Section II D.

- The Yukawa interactions mediated by neutral Higgs particles give the left-handed and right-handed fermions

$$u_{iR} = u_{iL} + h_u^0, \quad d_{iR} = d_{iL} + h_d^0, \quad e_{iR} = e_{iL} + h_d^0, \quad -\bar{N}_4 = \nu_{L,4} + h_u^0.\tag{37}$$

Since we consider  $T_{sp} < T_c$ , the Higgs condensation leads to  $h_u^0 = h_d^0 = 0$ . Consequently the left- and right-handed fermions have equal chemical potential. By the way, since we have shown that all families share the same chemical potential, in what follows the family indices will be buried.

- In addition, the vector-like mass terms together with their trilinear soft terms give

$$N_4 = -\bar{N}_4 = \nu_L, \quad \bar{L}_4 = -L_4, \quad \widetilde{N}_4 = -\widetilde{\nu}_{L,4} = -\nu_L.\tag{38}$$

So the dark sector particle asymmetry can be expressed with  $\nu_L$  and  $W^-$ .

- Finally, the EW sphaleron process leads that the left-handed fermions satisfy

$$3(u_L + 2d_L + \nu_L) = 0 \Leftrightarrow 3u_L + 2W^- + \nu_L = 0.\tag{39}$$

The vector-like doublets do not contribute to this equation since they do not contribute to the global  $U(1)_{B/L}$  anomaly.



Specified in the GMSB, all squarks share a larger mass  $m_{\tilde{q}} \sim \mathcal{O}$  (TeV), and the left-handed slepton masses  $m_{\tilde{\ell}}$  are several hundred GeV. So only the right-handed sleptons contribute at the leading order. On top of that, the vector-like particles are heavy and decouple also, except for a singlet spartner. In conclusion, we consider the effective field theory at  $T_{sp}$  with degree of freedoms SM+ $\tilde{N}$ .

Thus, four remained independent chemical potentials are for  $W^-$ ,  $u_L$ , and  $\nu_L$ . A further constraint comes from electromagnetic charge neutrality  $Q = 0$

$$Q = (6u_L - 6\nu_L - 16W^-) \frac{T_{sp}^2}{6} = 0, \quad (40)$$

where the heavy charged Higgs fields are not included here. Then from Eqs. (39) and (40), we obtain

$$\nu_L = -\frac{3(5 + 3f_{\tilde{e}_R})}{1 - 3f_{\tilde{e}_R}} u_L, \quad W^- = \frac{3(2 + 3f_{\tilde{e}_R})}{1 - 3f_{\tilde{e}_R}} u_L. \quad (41)$$

Now we can determine the asymmetries of baryon and AMP. At first, the final baryon number density (only including the SM quarks) is

$$n_B = 6(2u_L + W^-) \frac{T_{sp}^2}{6} = \frac{6(8 + 3f_{\tilde{e}_R})}{1 - 3f_{\tilde{e}_R}} u_L \times \frac{T_{sp}^2}{6}. \quad (42)$$

The dark sector carries  $B/L$  number, especially the AMP under consideration is nothing but a sneutrino system. So their asymmetry can be studied in light of the sneutrino-number, denoted as  $\tilde{\nu}_4$ . But as argued before the ordinary sneutrino can not remain asymmetry due to washing-out effects during decoupling (this part will translate into the SM lepton number rather than sneutrino number), and only the part stored in the dark sector can survive

$$n_{\tilde{\nu}} = 2f_{\tilde{\nu}} \times \tilde{\nu} \frac{T_{sp}^2}{6} = -\frac{6(5 + 3f_{\tilde{e}_R})}{1 - 3f_{\tilde{e}_R}} u_L \times \frac{T_{sp}^2}{6}. \quad (43)$$

In turn, according to the Eq. (7) the gravitino mass is predicted to be

$$m_{\tilde{G}} = \frac{\Omega_{\text{DM}} h^2}{\Omega_B h^2} \frac{8 + 3f_{\tilde{e}_R}}{5 + 3f_{\tilde{e}_R}} m_p \simeq 7.5 \text{ GeV}, \quad (44)$$

which does not depend on  $f_{\tilde{e}_R}$  much. This result is just as expected.

### C. Remarks on $U(1)_R$ -Symmetric MSSM

According to the analysis in Section II D, the gaugino/Higgsino mediated wash-out effects originate from  $U(1)_R$ -symmetry breaking in the MSSM. So, to forbid them, we are forced to turn to the  $U(1)_R$ -symmetric MSSM (MRSSM) [39]. Surprisingly, although starting from different point, we reach the same picture:  $U(1)_R$ -symmetric GMSB.

The accommodation of AMP is simple in the MRSSM, so we just make a short comment in this paper. In the MSSM, besides from the Majorana gaugino mass breaks  $U(1)_R$ , so does  $B_\mu$ -term. And then it is not enough to introduce the Dirac partner of gauginos [40], *i.e.*, the partners are  $U(1)_R$  neutral adjoint chiral superfields under SM gauge groups  $A = a + \theta\psi_A$ . We have to extend the Higgs sector by extra Higgs doublets with  $R$ -charge 2 [39], namely the  $(R_u, R_d)$ . Thus, the MRSSM Higgs sector is

$$W_{MRSSM} \supset \mu_u H_u R_u + \mu_d R_d H_d . \quad (45)$$

The Yukawa couplings are identical with those in the MSSM. Technically, the Higgsino mediated washing-out processes are forbidden by the separation between the  $(H_u, R_u)$  and  $(H_d, R_d)$ .

We have to stress that the vanishing Higgsino-mediated contribution can not be attributed totally to the exact  $U(1)_R$ . To see this, we consider the MSSM without  $B_\mu$ -term. The wash-out processes such as  $\tilde{f}_L f_R^* \rightarrow \tilde{f}_L' f_R'$  can proceed (with rates suppressed by Yukawa couplings). But the successful EW symmetry breaking excludes such a scenario. Thus, the exact  $U(1)_R$  can only be realistic in the MRSSM.

#### IV. CONCLUSION AND DISCUSSION

We considered the hybrid gravity-gauge mediated supersymmetry breaking where the gravitino mass is about several GeV. Interestingly, the strong constraints on the supersymmetry viable parameter space from the CMS and ATLAS experiments at the LHC can be relaxed due to the heavy squarks and gluinos, and it is consistent with null results in the DM direct search experiments such as XENON100. Especially, the possible maximal flavor and CP violations from the relatively small gravity mediation may naturally account for the recent LHCb anomaly. In addition, because the gravitino mass is around the asymmetric DM mass, we proposed the asymmetric origin of the gravitino relic density and solved the coincident problem on the DM and baryon densities  $\Omega_{DM} : \Omega_b \approx 5 : 1$ . The gravitino relic density arises from asymmetric metastable particle (AMP) late decay. However, we showed that there is no AMP candidate in the MSSM due to the robust gaugino/Higgsino mediated wash-out effects. Interestingly, AMP can be realized in the well motivated supersymmetric SMs with vector-like particles or continuous  $U(1)_R$  symmetry.

Some open question can be explored further to realize the “asymmetric” gravitino framework. For example, we can not exclude the other possibility in the non-standard cosmology, namely large individual flavor lepton asymmetry is presented when AMP, *e.g.*, the sneutrino freeze-out (below  $T_{sp}$  so baryon asymmetry can be small). As a consequence, the equilibrium with cosmic background does not imply the wash-out effects at all.

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## Note added

After the completion of this work, we noticed the paper [41], which also studied the Majorana LSP from the AMP late decays in the supersymmetric models. However, they considered the Bino dark matter.

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